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1 "Improved Process Monitor"

2
3 This invention relates to the field of the deposition,
4 removal or modification of thin films and/or substrate
5 materials.
6

7 Thin films are commonly used to modify surface
8 properties, and processes occurring in vacuum apparatus
9 are commonly used to deposit/remove or modify these
10 films and for some applications this modification
11 extends to the underlying substrate material. Typical
12 applications include the coating of optical components
13 to improve their light transmission or reflection
14 properties, the coating of composite materials to
15 improve adhesion behaviour, the coating of
16 semiconductors to introduce insulating, conducting or
17 indeed other layers with specific electronic, optical,
18 magnetic or mechanical properties, and the production
19 of ultra-small three dimensional structures for use in
20 sensors and computer based recording devices.

21 Typically these films and structures will have
22 dimensions from $1\mu\text{m}$ to several hundred microns.
23 Frequently the films are structured in stacks where
24 there is a change in chemical composition from one
25 layer to the next. Such stacks vary from the simplest

1 of one material on top of another to several hundred
2 different layers in sequence.

3

4 In order for these structures to carry out the function
5 for which they have been designed these materials
6 frequently have to be etched, deposited or, once having
7 been deposited, have to be removed or transformed (eg
8 annealed) wholly or partially with very great
9 precision. This deposition or removal is frequently
10 carried out under conditions of vacuum using
11 temperature controlled environments and gas or gases
12 excited into the plasma state. It is beneficial to
13 carry out measurement in-situ of the deposition or
14 removal. Such processes generate considerable
15 quantities of electrical, thermal, optical, vibrational
16 and Radio Frequency noise.

17

18 This invention improves the process control of these
19 deposition, etch or modification processes under these
20 inherently noisy and difficult conditions.

21

22 In this field it is already known that the light
23 emitted from a plasma may be used to determine the
24 composition of the active species and the chemical
25 concentration occurring at any particular time
26 (Goffered G.G., SPIE Vol 1392, p454-p459). The
27 described technique of measurement for process control
28 is preferred by many users over alternatives such as
29 quartz crystal microbalance or resistivity measurements
30 or the like in that it is non-invasive, but as
31 indicated below, it suffers considerable problems with
32 noise. Alternative non-invasive techniques such as
33 laser reflectometry (JVSTE 12 (6)p3306 '94 and
34 WO98/07002) exist but they demand the careful set up of
35 a light source reflecting from the sample and can limit
36 the geometry of the processing chamber or the location

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1 of ancillary equipment. Mass spectrometry provides an
2 alternative but it has the disadvantage of requiring to
3 extract a sample for analysis which has concomitant
4 problems with individual lifetimes of particular
5 chemical species.

6
7 In its simplest form the spectral emission method
8 provides a convenient remote measurement technique so
9 that if it is tuned selectively to measure the
10 concentration of element 'A' and an etch process is
11 occurring to remove films consisting predominantly of
12 element 'B' placed on top of and obscuring a substrate
13 consisting of element 'A', then when the etch reaches
14 down through all of the overlying film the signal
15 representative of element 'B' will fall to a very small
16 value to be replaced by a signal representative of
17 element 'A'. This idealised 'step change' in the
18 signal is in principle very easy to detect and a simple
19 level change algorithm will allow automatic detection
20 of the breakthrough point and thus automation of the
21 film removal process. The establishment of several
22 tuned channels of measurement (which may be realised as
23 individual channels or a multiplexing scheme) permits
24 simultaneous measurement of a number of characteristic
25 spectral outputs which can help in discrimination.

26
27 The above known art has the disadvantage that the
28 signal change is frequently not a simple abrupt step.
29 Furthermore pulsed processes are being used more
30 commonly now in order to improve process efficiency.
31 In addition the frequency profile of the signals
32 themselves may form complex shapes with either a lot of
33 fine detail (in the form of many lines) or alternatively
34 with very little fine detail (in the form of a
35 continuum). The nature of the physical situation is
36 therefore such that the exact determination of a

1 process endpoint achieving good run-reproducibility
2 requires extensive calibration and a high level of
3 skill on the part of the process technician setting up
4 the process control using spectral emission from the
5 plasma etch, deposition or surface modification
6 process. It is the objective of this current invention
7 to provide for improved process control using spectral
8 emission from a plasma process.

During the process some skilled operators will examine the behaviour in time of the emitted light characteristic of a particular constituent component in the plasma in an attempt to compare it to the behaviour that they noted during the calibration procedure. This relies on the constant presence of the operator and is not repeatable between operators.

18 From one aspect the invention consists in a method of
19 automatically determining the progress of plasma
20 processing including continuously monitoring a
21 predetermined frequency or frequency band of radiation
22 emitted from or absorbed by the plasma, developing a
23 graphical or numerical output corresponding to the
24 level of emittance or absorption, and electronically
25 comparing that output with a predicted output or
26 predicted trend to provide an indication of the
27 progress of the process.

29 From another aspect the invention consists in a process
30 control system for controlling a plasma based process
31 including means for continuously capturing a frequency
32 limited sample of radiation from a plasma, a detector
33 for producing an output indicative of the time varying
34 intensity of the radiation, and shape recognition means
35 for comparing the output against a predicted output or
36 trend to provide an indication of the progress of the

[illegible]

1 process.

2

3 From another aspect the invention consists in a process
4 control system for controlling a plasma based process
5 including means for continuously capturing a
6 predetermined range of frequencies and prior to
7 conversion to an electrical signal using a shape
8 recognition means to identify characteristic shapes in
9 the spectral domain. The refined signal is then
10 incident on a detector means for producing an output
11 which is indicative of the time varying intensity. A
12 shape recognition means is then employed in the time
13 domain for comparing the output against a predicted
14 output or trend to provide an indication of the
15 progress of the process.

16

17 From another aspect the invention consists in a process
18 control system for controlling a plasma based process
19 including means for continuously capturing a
20 predetermined range of frequencies and after their
21 incidence on a detector means using a shape recognition
22 means to identify characteristic shapes in the spectral
23 domain. The refined signal is then indicative of the
24 time varying intensity. A shape recognition means is
25 then employed in the time domain for comparing the
26 output against a predicted output or trend to provide
27 an indication of the progress of the process.

28

29 From a still further aspect the invention consists in a
30 process control system where a time evolving spectral
31 output from a plasma is detected by a spectral
32 detection means and then used in combination with the
33 application of shape recognition techniques to provide
34 a continuous measure of process progress against a
35 predicted trend.

36

1 Thus in embodiments of the invention the spectral
2 output of the plasma system is being monitored by shape
3 recognition techniques. Filters can be established in
4 the time, frequency and optical frequency domains which
5 respond to particular characteristic forms. The
6 predicted signal behaviour is examined for these
7 characteristic forms prior to running the process
8 yielding a data set that is indicative of process
9 progress towards an endpoint. During the process run
10 that is required to be automated the actual data train
11 is interrogated by the same shape recognition filter
12 set yielding a pointer position against the predicted
13 behaviour which is constantly updated permitting
14 complete access at all times to a measure of status of
15 the etched position or other process.

16
17 While further modifications and improvements may be
18 made without departing from the scope of this
19 invention, the following is a description of examples
20 of the invention, referring to the drawings, in which:

21
22 Fig. 1 shows the typical optical transmission of a
23 thin film filter;

24 Fig. 2 shows the typical optical transmission of a
25 'Fabry-Perot' etalon;

26 Fig. 3 shows the typical optical transmission of
27 the combination of a thin film filter with a
28 'Fabry-Perot' etalon;

29 Fig. 4 is a schematic illustration of a preferred
30 embodiment of the apparatus of the invention;

31 Fig. 5 shows a typical output signal from a
32 detector of the apparatus of Fig. 4;

33 Fig. 6 is a flow chart illustrating data
34 processing carried out in one form of the
35 invention;

36 Fig. 7 illustrates an alternative embodiment of

data processing.

Fig. 8 is a graph illustrating a modified application of the invention; and
Fig. 9 illustrates graphically a further modification.

Referring particularly to Fig. 4, in a typical process a silicon substrate 11 to be etched is masked with a two-dimensional pattern of photo resist and containing within the depth of the silicon structure a buried layer of silicon oxide, in a manner well known per se. The substrate 11 is placed in a plasma reactor system comprising a vacuum vessel 8 which is provided with vacuum pumping means (not shown) and electrodes 9 and 10. The substrate 11 is placed close to or on one of the electrodes 9, 10.

The etch system is provided with a plasma excitation means 6 and a gas control means 7. In the preferred embodiment at least one of these is pulsed so as to provide a cyclically varying environment in the vacuum chamber 8.

A window 12 allows optical radiation from the plasma to be incident on a mechanism which is provided for computing a particular spectral line of the plasma emission and consisting of a thin film filter 13 which is followed by 'Fabry-Perot' etalon 14 that has been suitably adjusted to isolate radiation that shows cyclical behaviour characteristics of the particular process. The output of 'Fabry-Perot' etalon 14 is incident on a detector means 15 which produces an output indicative of the instantaneous intensity of the selected spectral frequency. The detector means 15 then passes its output signal to a signal processing means 16 within which shape recognition algorithms

1 analyse the signal and produce a control signal to
2 indicate when a predetermined event has occurred or to
3 produce a continuous report on the progress of the
4 process.

5
6 As seen in Fig. 1, the narrow band filter 13 provides a
7 convenient means for isolating a particular spectral
8 line but in general it is not precise enough in its
9 response to isolate a particular line to the exclusion
10 of other lines that may interfere with it. The typical
11 band pass 1 of such a filter is approximately 5
12 nanometres.

13
14 The 'Fabry-Perot' etalon 14 on the other hand, as seen
15 in Fig. 2, provides a very sharp spectral response but
16 also allows adjacent sharp responses which are
17 relatively close in frequency terms. The individual
18 optical passbands are typically very narrow at about
19 0.2 nanometer but there is a multiplicity of them
20 separated at typically 10 nanometres.

21
22 The combination of the two elements, Fig. 3, provides a
23 means for convenient isolation of particular spectral
24 lines. With suitable angle tuning of the 'Fabry-Perot'
25 etalon, a single narrow passband is obtained at a
26 frequency characteristic of the etch process being
27 monitored.

28
29 Suitable thin film filters and 'Fabry-Perot' etalons
30 will be readily apparent to those skilled in the art.
31 As one example, suitable elements are those available
32 from Melles Griot Technical Optics Limited of Onchan,
33 Isle of Man. Likewise, the detector may be any
34 detector suitable to handle the optical output; as one
35 example, we have used a photomultiplier tube by
36 Hamamatsu.

1 Gaseous precursors are chosen so that with one
2 particular concentration of components and with
3 particular levels and bias of Radio Frequency or
4 microwave power the silicon material is etched. With
5 reference to the cyclic etch/passivation method of
6 forming features in the workplace, the etch and
7 passivation steps are discrete; see for example
8 published PCT application WO-A-9414187, the contents of
9 which are hereby incorporated by reference.

10
11 The output signal from the detector 15 (Fig. 5) shows a
12 characteristic wavetrain in time consisting of
13 repetitive double peaks. The repetitive signal is due
14 to the cyclical nature of the process. The distinctive
15 double peak shape is due to the etch of polymer
16 followed by the etch of silicon. The overall signal is
17 superimposed on noise from a variety of sources
18 including optical noise and time jitter pulsing when a
19 deposition/etch cycle is used. The characteristic
20 shape of the time development of the spectral line
21 signal is provided by an array of digital filters with
22 impulse responses matched to the characteristics of the
23 different time epochs. This array of filters can be
24 progressive and examine longer time segments as the end
25 point of the process approaches. The historical match
26 to longer segments of characteristic signal shape
27 increases the confidence of measure of exactly where in
28 the process progression the etch is at any particular
29 time.

30
31 More specific examples of the shape recognition process
32 will now be described.

33
34 Referring to Fig. 6, which illustrates in flow-chart
35 form the data processing carried out in the preferred
36 embodiment, an idealised prediction of the signal

1 obtained from the process scanned by a data window 91
2 which, in the preferred embodiment, may be a data
3 window extending to 1/3000 of the data size. The
4 contents of the data window 91 are then passed to a
5 software routine 92 that analyses frequency. In the
6 preferred embodiment this is a Fast Fourier Transform.
7 The output of the Fast Fourier Transform 92 is then
8 used to construct an adaptive digital filter 93 that
9 passes the frequencies present as being predicted to be
10 present in the data window 91 and highly attenuates
11 other frequencies. The output of the digital filter 93
12 is recorded as the processed signal against time 94.
13 The digital filter 93 is then used to carry out a shape
14 recognition 95 as compared to the idealised prediction
15 90. In the preferred embodiment this shape recognition
16 95 may be accomplished by a correlation of the Fourier
17 spectrum of the processed signal against the Fourier
18 spectrum of the idealised signal. The output of the
19 shape recognition 95 then yields a best match which is
20 the parameter 96 at any point in time of the processed
21 signal. This value is then compared to the target
22 process condition to give a termination On/Off
23 decision. Also this value is compared at 98 to time to
24 give a rate signal which may be used for closed loop
25 process control.

26
27 If there is inadequate knowledge of the process to
28 allow a full idealised signal to be produced, the shape
29 recognition may be achieved by a calibration run. In
30 Figure 7 the unprocessed signal output 100 of an etch
31 process is then processed by a digital filter 101 using
32 filter parameters derived from keyboard entry 102. The
33 output of the digital filter 103 is then compared to
34 any predictive modelling or prior experience of film
35 shape to ensure that representative features are
36 present. This processed calibration run is then

1 calibrated against a desired etch by an off-line
2 technique such as stylus profiling. The resulting
3 calibration data set 105 is then used in exactly the
4 same way as the idealised signal data set 90 in the
5 previous preferred embodiment.

6
7 The skilled reader will understand that the method for
8 analysing frequencies may be of many different types
9 such as cosine, sine or Laplacian methods. The skilled
10 reader will also understand that the shape comparison
11 technique may be achieved by many techniques including
12 Laplace Transforms and Gradiometer Transforms. The
13 data windows may also be of varying extent. The data
14 set that is to be compared to, which may be an
15 idealised data set resulting from a model or a
16 calibration data set, is used in conjunction with a
17 range of data windows. These data windows increase in
18 length from one to the other so that if confidence of
19 recognition of shape by a correlation technique using
20 the Fast Fourier Transform or a Laplacian Technique, or
21 application of any other shape recognition method such
22 as the Gradiometer Transform, falls below a pre-defined
23 minimum level then the subsequent increased size window
24 may be used. Use of a data window of increased size
25 has the advantage of allowing more data to be used to
26 recognise features. It has the concomitant
27 disadvantage that more data has to be present in the
28 processed data stream to allow a meaningful comparison
29 but, since the movement to a larger data window only
30 occurs after more processed data has been already
31 collected, this disadvantage has no impact on the
32 availability of process data. Under circumstances
33 where it is desirable for the confidence of fit to be
34 very high, it may be desirable to use data windows only
35 varying by a very small amount from each other and to
36 automatically change from one data window to the

1 subsequent one rather than waiting for an inadequate
2 fit to be recorded.

3
4 It should be understood that although the example cited
5 is that for cyclic (etch/passivation) etching of
6 silicon, other materials can be etched or other plasma
7 process performed under the control of the present
8 method and system.

9
10 The advantages of the invention are that the use of
11 shape recognition techniques automates the plasma
12 process allowing for unattended operating and the rapid
13 commissioning of process. A further advantage of the
14 technique is that use of the shape and trend of the
15 curve as opposed to traditional level discrimination
16 increases the immunity of the measurement to noise
17 source including shot to shot noise arising from time
18 jitters in a pulsed process. A further advantage of
19 the technique is that the shape recognition method
20 yields a confidence of fit at all points along a
21 predicted curve which in addition to endpoint detection
22 provides measures which can be used for continuous
23 optimisation of the process parameters.

24
25 A further advantage is that light from the plasma can
26 be obtained at a wide variety of locations, so the
27 system does not inhibit chamber design. Indeed, the
28 input for the filter 13 could be brought from the
29 chamber in an optical fibre.

30
31 Instead of using the spectral emission of the plasma,
32 it is possible to use the spectral absorption by the
33 plasma or by reaction species or product species of a
34 defined light source, such as a frequency swept laser.
35 This is used to produce a time-varying signal, which is
36 analysed in the same way.

1 As a further example of the invention if the spectral
2 output that is characteristic of the process
3 development is not an atomic spectral line (Fig. 8) but
4 rather a vibrationally broadened molecular series of
5 lines then a particular example of the use of shape
6 recognition techniques in the spectral domain is to
7 search for the existence of this species by the use of
8 an element which responds to the characteristic form.
9 A vibrationally broadened molecular series has a
10 spacing which is characteristic and constant in
11 wavenumbers. Conveniently the 'Fabry-Perot' etalon has
12 a series of passbands which are also linearly separated
13 in wavenumbers. Therefore a specifically designed
14 'Fabry-Perot' etalon conveniently implements the shape
15 recognition technique in hardware rather than software.
16

17 As a further example of the invention if the spectral
18 output that is characteristic of the process
19 development is as a result of chemical reaction between
20 reactants produced as by-products of the main plasma
21 process then such chemiluminescent spectral output is
22 likely to form a broad continuum spectral feature. A
23 convenient implementation of the shape recognition
24 technique (Fig. 9) in the spectral domain is to take a
25 rapid wide-band spectral measurement and then apply a
26 shape recognition algorithm in the spectral domain
27 which algorithm is derived from the specific envelope
28 function form characteristic of the wide band
29 chemiluminescent signal of the particular reaction that
30 is required to be monitored. Such an approach allows
31 strong signals derived from specific plasma processes
32 to be eliminated prior to examination of the signal for
33 its time behaviour.
34